ERUPTIVE HISTORY OF THE ELYSIUM VOLCANIC PROVINCE OF MARS

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New geologic mapping of the Elysium volcanic province at 1:2,000,000 scale and crater counts provide a basis for describing its overall eruptive history. (We counted craters larger than 2 km in diameter to achieve optimal consistency; accurate counting of smaller craters is adversely affected by apparent variations in density due to secondaries, volcanic pits, image quality, and erosion.) The following stages are described in order of their relative age; they are also distinguished by eruption style and location.

Stage 1: Central volcanism at Hecates and Albor Tholi

These volcanoes are embayed by lava flows from Elysium Mons. This relation, as well as crater densities (Table 1), supports an Upper Hesperian surface age [1]. We have no evidence to determine when these volcanoes became active. Their steep slopes indicate that they are composed of once-viscous lava or interbedded lava and pyroclastic material [2,3]; no lava-flow scarps were identified.

Stage 2: Shield and complex volcanism at Elysium Mons and Elysium Fossae

The vast majority of exposed lava flows in the region were extruded from Elysium Mons and nearby fissures. The flows overlie Lower Hesperian ridged plains material in eastern and southwestern Elysium Planitia and polygonally grooved material west of the Elysium rise [4]. The extent of the flows is more clearly defined on Viking than on Mariner 9 images [5], but in some areas, such as northeast of Hecates Tholus, the flows and smooth plains material appear to intergrade. We divided the area of the unit into 27 $5° \times 5°$ sections each covering 65,000 to 75,000 km^2. The average count (Table 1) indicates that the flows are lowermost Amazonian, and variance in the counts allows placement of many of the flows in the Upper Hesperian. Individual counts range from $N(2)=278\pm61$ to 508 ± 84 (craters >2 km diameter per 10^6 km^2), and only three areas have crater densities whose standard-deviation limits do not overlap with the standard-deviation limits of the average count. Elysium Mons itself has a crater density of about N(2)=350, which corresponds to a slightly younger stratigraphic position than indicated by previous N(1) counts [3,6]. Because of the uniformity in crater densities and the fair to poor quality of images in some areas, we could not distinguish flow sequences of different periods in most cases. One exception is south of Eddie crater, where its ejecta have prevented the burial of precrater flows by younger flows.

The morphology of the flows of this Elysium sequence is about the same as those of the widespread flow units (members 1 to 5) of the Tharsis Montes Formation [7], which are Late Hesperian to Middle Amazonian in age [1]. The generally large volumes, lengths, and thicknesses of the flows indicate that they result from high rates of eruption of low- to moderate-viscosity lava. Thickness of the flow sequence is a few hundred meters in distal areas, where they partly bury impact craters several to tens of kilometers in diameter that were formed on older surfaces [8]; near Elysium Mons, where such impact craters are apparently completely buried, flows are perhaps more than a kilometer thick.

The flows mostly originated from the northwest-trending fractures of Elysium Fossae and fractures circumferential to Elysium Mons. Some fractures, perhaps where eruption rates were particularly high [9], developed into sinuous rilles or depressions. These features are mostly found west of

Elysium Mons, along with small domes, eroded flows, and crenulated ridges. The ridges and some of the domes may be eruptive features of high-viscosity lava. Other domes have summit craters and resemble cinder cones. These domes, as well as the eroded flows, may be composed of pyroclastic material resulting from the interaction of ground ice with erupting magma.

High up on Elysium Mons, lava flows are shorter, narrower, and less common than those in lower areas. Their smaller size indicates that they were erupted at lower extrusion rates. They resemble flows that are common high on Olympus Mons and Tharsis Montes. Also found on Elysium Mons are sinuous ridges that generally trend downslope; they are prominent on the north flank of the shield. Other sinuous ridges interfinger with flows south of Elysium Mons and west of Albor Tholus. Their origin is uncertain, for they resemble neither wrinkle ridges (of structural origin), nor ridges (of lava-flow or debris-flow origin) having collapse pits and channels on their crests. Perhaps the sinous ridges formed by eruption, flow, and erosion of pyroclastic material.

Also apparently associated with this stage of volcanism are vast eroded and channelized flows in Utopia Planitia [10]. Their origins have been ascribed to debris flow [11] and pyroclastic flow [10] caused by volcano-ice interactions.

Stage 3: Rille volcanism at Elysium Fossae and Utopia Planitia

After an apparent hiatus in volcanic activity, several large rilles of northwesternmost Elysium Fossae extruded lavas that flowed northwestward into Utopia Planitia. Morphologies of these flows range from voluminous sheet flows to thin, narrow flood lavas. Crater counts (Table 1) are approximate because the flows are not clearly distinguishable from older flows, and areas proximal to the rilles have fewer craters. Also, age relations with Utopia flows are unclear; some of the thicker Utopia flows originating from Elysium Fossae appear coeval with the lava flows. These Utopia flows themselves may have a volcanic origin related to this period of activity. Given these relations and the crater counts, we tentatively place these lavas and Utopia flows in the Lower and Middle Amazonian Series.

Stage 4: Flood-lava and pyroclastic eruptions at Hecates Tholus and Elysium Mons

A virtually uncratered area west of the summit of Hecates Tholus was postulated to be mantled by a pyroclastic air-fall deposit [12]. The lack of craters suggests an Upper Amazonian position. Similarly, on Elysium Mons, an oblong area 60 x 90 km surrounding the summit caldera and extending to the north and west appears to be mantled by a thin, low-albedo deposit (on images taken at low sun-incidence angles). The edge of the deposit is composed of fingerlike extensions radiating downslope. We speculate that this deposit is composed either of thin pyroclastic flows or air-fall deposits that have subsequently moved downslope along talus chutes.

On the west flank of Elysium Mons are several patches of sparsely cratered, very young flood lavas. Although they resemble the flows described by [9], we distinguish three separate areas, two of which occur outside the area mapped by [9]. Similarly, most of the youngest flows of Olympus Mons and Tharsis Montes appear to be thin flood lavas. Very young lavas also have been postulated to make up smooth plains in the southern part of the Elysium region [13]; however, we believe that this area is mostly covered by channel material [10,14].

Discussion

Tectonic and channeling activity in the Elysium region is intimately associated with volcanism [9,10,14]. Recent work [8,15] indicates that isostatic uplift of Tharsis, loading by Elysium Mons, and flexural uplift of the Elysium rise produced the stresses responsible for the fracturing and wrinkle-ridge formation in the region. Coeval faulting and channel formation almost certainly occurred in the pertinent areas in Stages 2 to 4. Older faults east of the lava flows [8] and channels on Hecates Tholus may be coeval with Stage 1. Also, these stages show that the viscosity of erupted magma has decreased over the eruptive history of Elysium, as it has at Tharsis, perhaps indicating that the magma originated from progressively deeper sources.

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Table 1.
Crater Densities and Stratigraphic Positions of Elysium Volcanic Units

Unit	Crater density $N(x)$ = no. > x km diam./10^6 km^2	Stratigraphic series
Hecates Tholus mantle	no fresh craters observed [12]	Upper Amazonian
Elysium Mons mantle	few kilometer-size craters	Upper Amazonian
Elysium flood lavas	few kilometer-size craters	Upper Amazonian
Elysium Fossae--Utopia Planitia flows	N(2) = about 100-200	Lower Amazonian-Middle Amazonian
Elysium Mons flows		
all	N(2) = 378±15	Upper Hesperian-Lower Amazonian
shield	N(1) = 2350±153 [3]	
	N(1) = 1800-4800 [6]	
	N(2) = about 350	
Albor Tholus	N(1) = 1500±263 [3]	Upper Hesperian
Hecates Tholus	N(1) = 1800±351 [3]	Upper Hesperian
	N(1) = 1300-15,000 [6]	

Note: Stratigraphic series determined by crater counts and stratigraphic relations (see text).